Packaged Combined Heat and Power Technology Overview and Market Profile



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July 2023



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Energy and Transportation Science Division

PACKAGED COMBINED HEAT AND POWER TECHNOLOGY OVERVIEW AND MARKET PROFILE

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1. INTRODUCTION

Combined heat and power (CHP), sometimes referred to as cogeneration, is an efficient and clean approach to generating electric power and useful thermal energy onsite from a single fuel source, offering reliable and affordable energy services to businesses and institutions. Furthermore, CHP provides a costeffective opportunity to improve the environmental footprint and resilience of industrial and commercial facilities across the United States.

CHP equipment can be custom-engineered or installed as a predesigned and assembled package. A packaged CHP system is a standardized, pre-engineered system that includes all equipment, piping, wiring, and ancillary components¹ to deliver electricity and thermal energy to a host facility with minimal onsite engineering and design time. Packaged CHP systems can be shipped as single or multiple modules with standard interconnections (e.g., fuel; electrical; thermal—hot water, steam, and/or chilled water), which simplifies installation and reduces the costs associated with the project. Most containerized or single packaged CHP system offerings range from 10 kW to 3 MW in capacity.

Features of Packaged CHP Systems

- Standard design
- Prime mover, electrical generator, and heat recovery equipment included
- Control panel, piping, valves, and all ancillary equipment included
- Factory assembled and tested
- Enclosure provided
- Shipped to site ready for installation
- Capacities ranging from 10 kW to 3 MW

Packaged CHP systems are extending the operating, efficiency, and emissions benefits of CHP to nontraditional markets in commercial, institutional, multifamily, light manufacturing, government, and military applications. These markets tend to be served by smaller systems (less than 5 MW) that are conducive to pre-engineered packaging and/or modularization. Many of these sectors have limited CHP experience and technical resources to adequately evaluate, install, and maintain onsite CHP systems. The introduction of packaged CHP offerings from experienced CHP Packagers and Solution Providers has accelerated CHP adoption, lowered energy costs, reduced emissions, and strengthened energy resilience in these sectors.

In 2019, the US Department of Energy (DOE) launched the Packaged CHP eCatalog² to promote increased acceptance of efficient, cost-effective CHP in these applications. The Packaged CHP eCatalog³ is a web-based, searchable platform that hosts DOE-recognized packaged CHP systems with features designed to reduce economic and performance risks for designers, developers, owners, and facility operators interested in installing CHP. DOE established the Packaged CHP Accelerator⁴ at the same time to help launch and publicize the eCatalog, and to validate project performance, cost, and installation time of CHP packages across a variety of applications. Accelerator efforts documented installed cost

¹ Larger capacity packaged CHP systems may be divided into more than one skid-mounted sub-assembly to accommodate shipping constraints.

² https://betterbuildingssolutioncenter.energy.gov/resources/packaged-chp-catalog-ecatalog-fact-sheet

³ https://chp.ecatalog.ornl.gov

⁴ DOE Better Buildings Accelerators are public-private partnership programs designed to develop new strategies and practices to overcome barriers to clean energy deployment. https://betterbuildingssolutioncenter.energy.gov/sites/default/files/attachments/Packaged-CHP-Accelerator-Fact-Sheet-FINAL.pdf

reductions and installation time reductions of more than 20% for packaged CHP systems over 100 kW compared with custom-engineered systems.⁵

The Packaged CHP Accelerator and eCatalog established a peer-to-peer network connecting public and private sector partners including utilities, state energy offices, and energy efficiency program administrators interested in promoting cost-effective, efficient CHP systems, Packagers, and Solution Providers. Feedback from these partners, along with input from DOE's CHP Technical Assistance Partnerships (CHP TAPs)⁶, was critical in understanding the current market for packaged CHP technologies, stimulating investment in these technologies, and guiding future directions for packaged CHP systems and their applications.

This report provides background on packaged CHP systems, an overview of their benefits, a profile of current packaged CHP installations, and a summary of future market trends; this report is intended for facility owners, project developers, engineers, policymakers, and other stakeholders looking to increase the adoption of efficient, flexible, and resilient packaged CHP systems.

⁵ Based on analysis of data provided by NYSERDA on packaged CHP costs and installation times. This data set enabled a direct comparison of costs and installation times for custom-engineered CHP systems and packaged CHP systems from the NYSERDA CHP Program.

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⁶ https://betterbuildingssolutioncenter.energy.gov/chp/chp-taps

2. PACKAGED CHP BACKGROUND

The concept of CHP was first introduced in the late 1800s with the Pearl Street Station in Manhattan, New York, using steam engines to produce both electricity and steam heating for local buildings and manufacturers. CHP gained prominence in the late 1900s as an efficient power and thermal energy resource for large manufacturing facilities and institutional campuses. Most CHP systems were custom engineered for each application, depending on the electric and thermal requirements of the host facility. By the early 1990s, preassembled packaged CHP systems entered the US market, such as the 60 kW Tecogen system shown in Figure 1.

Early packaged CHP systems were designed based on reciprocating engine prime movers and over time, they grew to include microturbines and fuel cell packages, and ultimately modular combustion turbine systems. Much of the early demand for these products occurred in California



Figure 1. Packaged CHP system (60 kW).

and the northeastern United States, where electricity prices were high, creating favorable economics in smaller commercial buildings previously not associated with CHP installations. Throughout the 1990s, additional packaged CHP products entered the market; notably, larger (above 500 kW) capacity systems based on high electric efficiency, low-emission reciprocating engines manufactured in Europe. Several CHP Solution Providers in the United States started integrating these European engines into complete packages, and by the late 1990s, packaged CHP products were commonly available in capacities up to 1 MW.

By 2000, interest had increased in developing packaged CHP products fueled with renewable biogas resources in addition to natural gas. This interest was driven by tighter Environmental Protection Agency emissions requirements for farms and wastewater treatment plants, which led to packaged CHP systems being imported from Europe, where advanced engine development had produced the first commercially available reciprocating engines designed for biogas operation. For example, Figure 2 shows a Jenbacher containerized digester gas CHP system.



Figure 2. Packaged CHP biogas system (999 kW).

2.1 CHP INTEGRATED ENERGY SYSTEMS

DOE's Distributed Energy Program provided early R&D support for packaged CHP development in the early 2000s through the Integrated Energy Systems program. One of the R&D goals was to demonstrate the feasibility of integrated energy systems (IESs) in new customer classes, helping them reach 80% efficiency with customer paybacks of less than 4 years, assuming commercial-scale production. To develop IESs, researchers combined dissimilar subsystems so that they can work together to provide higher efficiency at a lower cost than if they were operated individually. As a result of the DOE R&D

support, IESs reached the marketplace with pre-manufactured or off-the-shelf capabilities, allowing systems to be scaled up or down or configured to serve a variety of applications. Such DOE-sponsored IESs are often called *plug and play* systems—that is, they are designed into a packaged system offsite, installed, commissioned with minimal onsite design and installation support, and replicated at numerous other sites at a reduced cost.⁷

Project Snapshot: The Ritz-Carlton Hotel, San Francisco, California⁷



Image courtesy of DOE Western CHP TAP.⁷

In 2005, the Ritz-Carlton Hotel in San Francisco installed a 240 kW Capstone MicroTurbine-based UTC Power Company PureComfort CHP packaged system to reduce peak demand, lower energy consumption, and reduce energy expenses for the hotel. The CHP package comprises four pre-engineered 60 kW units and a standardized absorption chiller and was developed under DOE's Integrated Energy Systems program. This CHP configuration meets 70% of the hotel's cooling demand and allows the hotel to save \$120,000 in energy costs annually.

2.2 NYSERDA'S CHP PROGRAM AND DOE'S PACKAGED CHP ECATALOG

In the early 2000s, the market demand for packaged CHP offerings grew as CHP incentive programs in California, Massachusetts, New York, and other states helped further encourage installations of packaged CHP products. In particular, the multi-stage New York State Energy Research and Development Authority (NYSERDA) CHP Program led to the development of a strong marketplace for standardized packaged CHP products in the Northeast. The first stage (2000–2008) was a NYSERDA-funded demonstration program that tested a variety of packaged and custom-engineered CHP approaches in a not-yet-mature market. With the success of the initial program, NYSERDA transitioned to its second stage, a performance-based incentive program (2007–2013). Systems that met operational efficiency requirements would receive incentive payments as they reached project milestones. The program required data monitoring of project operation for 2 years, with meters providing data to NYSERDA's publicly available website.

The first two stages of the NYSERDA CHP Program revealed that many custom-engineered systems were oversized, and most installations were quite similar in terms of the core system, with marginal differences in design choices. With standardized packaged systems, the process of installing CHP could be simplified, with standard designs and customization options to fit facility requirements. Purchasing decisions could be streamlined and simplified, with a focus on right-sizing to improve operational efficiencies.

In 2013, NYSERDA revamped its CHP Program, shifting focus to establishing the conditions for a self-sustaining market transformation to standardized packaged systems offering reduced costs and project

⁷ https://chptap.ornl.gov/profile/233/ritz-carlton-Project_Profile.pdf

timelines. A catalog of NYSERDA-reviewed and -verified packaged CHP products with predefined incentive payments by milestones⁸ was developed to assist New York customers in selecting the right CHP package for their application. A key objective for NYSERDA was to instill customer confidence in CHP by creating more informed end-users and developing a cadre of CHP providers who were able to consistently deliver quality outcomes. Program incentive levels were reduced over time on a regular published schedule, giving vendors time to adjust and ultimately create a successful and sustainable business model.⁹

The NYSERDA CHP Catalog provided a one-stop shop for potential end users, who could compare verified packaged systems offered by approved vendors. The CHP Catalog incentive program, which ended in December 2019, led to more than 400 packaged CHP installations in New York. The program also led to a vibrant marketplace for packaged CHP Packagers and product offerings that has expanded the packaged CHP market into other states, with packaged CHP installations growing substantially in New Jersey, Massachusetts, and California after 2013.

As the NYSERDA CHP Catalog incentive program drew to a close, DOE launched a national program to support deployment of efficient packaged CHP systems. DOE established the Packaged CHP eCatalog, a national web-based, searchable platform of DOE-recognized packaged CHP systems that meet certain efficiency and performance requirements, offered by DOE-recognized CHP suppliers and installers (eCatalog Packagers and Solution Providers). Building on the NYSERDA program, the DOE eCatalog was designed to increase the deployment of efficient, resilient CHP by

- ▶ Reducing perceived risks of installing and operating CHP by providing comparable performance data for commercially available packaged CHP systems;
- ▶ Promoting the use of replicable CHP systems that reduce design errors and limit uncertainty with the associated performance, time, and cost impacts; and
- Recognizing CHP packages that meet specific performance requirements provided by recognized CHP Packagers and Solution Providers.

A key lesson learned from the NYSERDA CHP Program was that developing and supporting a packaged CHP catalog by itself will not advance the CHP market. Market success required a robust market engagement program to educate end users on CHP and the benefits of packaged systems. The NYSERDA program was designed to make end users and design engineers aware of the CHP Catalog and qualified CHP suppliers, and to support end users with technical assistance and advice through the project implementation process. DOE initiated the Packaged CHP Accelerator program in parallel to the Packaged CHP eCatalog to engage industry stakeholders to similarly support the launch and promote the use of the national eCatalog. The Accelerator was used to build effective CHP market engagement programs in key market regions while working with the DOE CHP TAPs to provide technical assistance and demonstrate the benefits of packaged CHP.

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⁸ Starting in 2017, the program paid 33% of the incentive after completion of the design and all permit applications, 33% of the incentive when the CHP system was fully installed, and the balance of the incentive when the CHP system was fully commissioned and operational.

⁹ https://chptap.ornl.gov/profile/166/NewYorkCHPCatalog-profile.pdf

3. PACKAGED CHP BENEFITS

CHP systems are generally 40% to 60% more efficient than separate heat and grid power and can increase energy security by producing energy directly at the point of use. ¹⁰ CHP also advances climate and clean energy goals by reducing emissions of CO₂ and other pollutants. CHP improves resilience by maintaining baseload power and thermal energy for end users during prolonged grid outages. Packaged CHP systems provide the same benefits as custom-engineered CHP systems, with additional advantages in reduced cost, installation time, and system complexity.

Packaged CHP systems are defined by their preinstalled components and incorporate a variety of prime mover technologies, including reciprocating engines, microturbines, combustion turbines, and fuel cells. Manufacturers design and build standardized systems that can be used in many different settings, rather than designing and engineering a new system for each location. These units are tested and preassembled before they arrive skid-mounted, containerized, or in multiple modules with standard installation requirements.

One of the main attributes of packaged CHP systems is that they are standardized, meaning they are built and delivered in accordance with published specifications. Standard packages can easily match site criteria, such as voltage and frequency, hot water supply temperature, ambient weather conditions, and altitude. This approach streamlines many elements of the procurement process, including equipment selection, financial analysis, site-specific engineering, permitting, and site modifications. Additionally, system installation is simplified, with site-specific engineering typically limited to designing connections to the fuel supply, water supply, thermal loads, electrical system, and building control system. As a result, the cost and time to complete an installation can be significantly reduced compared with customengineered CHP systems. With lower installation and engineering costs, as well as shorter project timelines, packaged systems can provide a higher return on investment than traditional custom-engineered CHP systems.

Packaged CHP Solution Providers also offer standardized maintenance contracts to help customers who may not have qualified staff to operate and maintain the system. The relative ease of installing packaged CHP systems, coupled with complete service and maintenance contracts, reduces the real and perceived risks for end users and can lead to increased deployment of packaged systems across many sectors.

Key features of packaged CHP systems include the following:¹¹

- ▶ Modular design: Because of their modular design, packaged CHP systems can be installed as single units, or as multiple units connected to create larger capacity systems. Systems using multiple modular units have numerous benefits:
 - Multiple-unit installations can be more efficient than single-unit CHP systems. CHP systems lose efficiency when operated at part-load to follow load fluctuations. In multiple-unit installations, individual units can be shut down to reduce system output, allowing remaining units to operate near full capacity at higher efficiencies.
 - O Systems using multiple units can improve reliability and system availability since one unit can be taken offline for maintenance while the others continue to operate.

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¹⁰ https://betterbuildingssolutioncenter.energy.gov/sites/default/files/attachments/DG%20for%20Resilience%20Planning%20Guide%20-%20report%20format.pdf

¹¹ https://www.epa.gov/sites/default/files/2017-09/documents/catalog-of-chp-technologies-section-7.pdf

- Additional units can be added over time to increase capacity if electrical or thermal loads increase.
- ▶ **Replicability:** As an off-the-shelf product, a packaged CHP system installed at one facility can be installed in the same way at similar facilities (e.g., hotel chains).
- ▶ **Quality control:** A packaged CHP product is factory-built based on a standard design, which expedites high-quality manufacturing/assemblage.
- ▶ **Pre-shipment testing:** The packaged system is tested at the factory prior to shipment, ¹² which minimizes field testing and potential field rework.
- ▶ **Accountability:** A single CHP Solution Provider can be responsible for all aspects of the project (i.e., design, engineering, commissioning, operation/control, and financing), which minimizes potential conflicts.
- **Service:** The CHP Solution Provider can be a "one-stop shop" for all service and maintenance.
- ▶ Warranties and performance guarantees: A single source, the CHP Solution Provider, is responsible for all warranties and performance guarantees.

Customers can choose several options for packaged CHP systems to meet their specific site requirements, including the following:¹¹

- ▶ Type of prime mover (engine, microturbine, combustion turbine, or fuel cell)
- ► Thermal output (steam, hot water, chilled water, or combination)
- ► Type of generator (synchronous, induction, or inverter)
- ► Generator voltage and frequency
- Black start/islanding capability
- Enhanced sound attenuation
- Additional emissions controls
- ▶ Specialized heat recovery options, such as an absorption chiller to produce chilled water for cooling applications or a steam boiler to make steam from the prime mover exhaust

¹² Some systems cannot be factory-tested because of size limitations; nevertheless, all system components are tested and the packaged system is pre-engineered and designed to perform as stated.

Third-Party Financing of Packaged CHP Systems

CHP systems (both packaged and custom-engineered) are frequently offered as part of a full-service package. The Solution Provider installs, operates, and maintains the equipment, which is fully financed by either the developer or a third-party financier. The standardization of packaged systems simplifies this process because financiers can see a demonstrated track record of identical systems operating successfully in similar applications. Furthermore, the system is properly operated and maintained by a third party familiar with the equipment, lowering the likelihood of future performance issues. All these advantages serve to lower the cost, complexity, and installation time of CHP systems, making them more accessible to potential end users in all sectors.

3.1 PROJECT IMPLEMENTATION BENEFITS

Implementation of a successful CHP project involves the following steps, all of which are facilitated by standardized CHP packages.

1. **Planning:** The customer establishes the facility's electric and thermal requirements and evaluates onsite energy options including packaged CHP equipment. Preliminary cost and performance estimates are applied to assess project viability. *Packaged CHP systems offer standard inputs, outputs, and performance specifications to facilitate this process.*

CHP Technical Assistance Partnerships

Prospective CHP users can reach out to the DOE regional CHP TAPs to receive fact-based, non-biased engineering support to evaluate the opportunity for CHP at their site. As leading experts in CHP, the 10 CHP TAPs provide technical services and assistance that helps maximize the economic impact and reduce the risk of CHP from initial screening through project implementation.

- 2. **Vendor selection:** The customer issues a request for proposals (RFP). The RFP specifies required system performance, all hardware deliverables, and the allowed time frame for completing the installation. Based on evaluating proposals, the customer selects a single CHP vendor. *Packaged CHP systems listed in a resource such as the DOE Packaged CHP eCatalog can streamline the RFP and selection process compared with custom-engineered projects by reducing the amount of time and effort spent reviewing system design and vendor capabilities.*
- 3. **Construction:** After the customer issues a purchase order, the CHP Solution Provider is responsible for site construction, including project management and construction management. For packaged CHP systems, the Packager assembles the package and factory tests the product before shipping the CHP package and ancillary hardware to the site. This minimizes field design and assembly, where cost and complexity can escalate and where problems often arise.
- 4. **Commissioning:** After the CHP system is fully installed, the Solution Provider is responsible for all start-up and commissioning. In this step, the Solution Provider will demonstrate that the CHP system meets or exceeds performance guarantees. *Packaged CHP systems are assembled through a standard process to ensure accurate performance specifications and pretested at the assembly facility, simplifying onsite commissioning.*
- 5. **Operation:** After the CHP system is commissioned, the Solution Provider can hand off the system to the customer for operation. Maintenance is frequently outsourced, especially time-sensitive or complicated maintenance, such as outage recovery, prime mover overhaul, and emission control servicing. *Packaged systems are typically offered with standard maintenance contracts*.

3.2 COST AND TIME REDUCTIONS FROM PACKAGED CHP

Packaged CHP systems offer the opportunity for reduced costs and project timelines because of their simplified engineering and installation processes, as noted previously; one objective of the Packaged CHP Accelerator was to document and verify these potential benefits. However, these advantages can be difficult to quantify without a basis of comparison. Reviewing the available sources of CHP installation data indicated that packaged and custom-engineered CHP systems would need to be compared on a common basis to properly assess the impacts on installed costs and project timelines, requiring access to clear and consistent data of both packaged and custom-engineered CHP projects. The only source of such data was the NYSERDA CHP Program, which gathered project cost and project development time data for both packaged and custom-engineered CHP projects from 2000 to 2019. Since the NYSERDA CHP Catalog incentive program was limited to packages up to 1.3 MW in capacity, the prime mover technologies were limited to reciprocating engines and microturbines.

NYSERDA provided access to its data on project cost, installation times, and performance from more than 400 CHP systems installed through its program, from the early demonstration projects (2000–2008) to performance-based incentives (2007–2013) to the NYSERDA CHP Catalog (2013–2019). DOE used this information to assess the differences in costs and installation times between packaged and customengineered CHP installations.

Data on custom-engineered systems installed in the early stages of NYSERDA's CHP Program were compared with data on packaged CHP systems from the CHP Catalog. Available data were heavily weighted toward packaged CHP systems because of the limited number of applicable custom-engineered projects and the fact that the CHP Catalog acted as a catalyst for the packaged CHP market, driving hundreds of new installations in New York. After removing outliers and projects with atypical installation requirements, data on 23 custom-engineered systems from 2003 to 2015 were compared with data on 310 packaged CHP systems installed from 2013 to 2021.

The data set of custom-engineered systems consisted of 22 reciprocating engines and 1 microturbine, with 15 systems sized 101–300 kW and 8 sized 100 kW or smaller. Cost and installation time data were compared with the 310 packaged CHP systems (255 reciprocating engines and 55 microturbines, covering a wide range of system sizes). Because of limited data for other prime mover technologies, the analysis focused on differences in costs and installation times for reciprocating engine packages.

To provide a direct comparison of similar installations, custom-engineered reciprocating engine systems in two size ranges (100 kW or smaller and 101–300 kW) were compared with packaged CHP engine systems in the same size ranges. By only comparing systems that were installed in New York, regional differences in the variability of installation costs and project timelines were minimized.

As shown in Figure 3, reciprocating engine packaged systems achieved significant cost reductions compared with custom-engineered engine systems in New York—a 31% decrease for systems 100 kW or smaller, and a 24% decrease in systems sized 101–300 kW. All costs were normalized for inflation at 2015 levels. Notably, these costs represent New York CHP installations, with the vast majority (21 of 22 custom-engineered and 231 of 255 packaged engines) located in New York City, where installation costs are high compared with other regions of the country because of high labor rates, code compliance costs, and zoning and construction requirements.

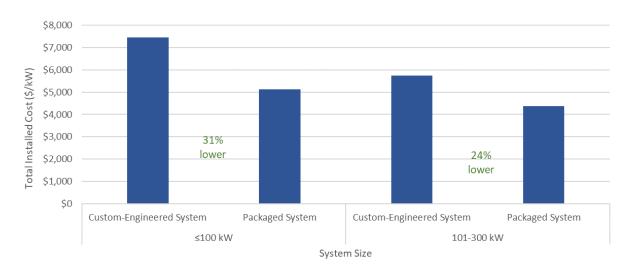


Figure 3. Cost reductions for packaged CHP vs. custom-engineered systems in New York.

Packaged CHP installations also had reduced timelines between the start of the project and final commissioning in New York compared with customed-engineered systems. As shown in Figure 4, project timeline reductions were most prominent in systems over 100 kW in size (22% reduction compared with 10% reduction for systems under 100 kW). Projects 100 kW or smaller had shorter installation times overall compared with systems above 100 kW because they tend to be less complex due to the nature of installations at smaller commercial buildings compared with larger facilities. Similar to costs, installation times in New York tend to be higher than the rest of the country because of complex permitting processes for code compliance and zoning and construction.

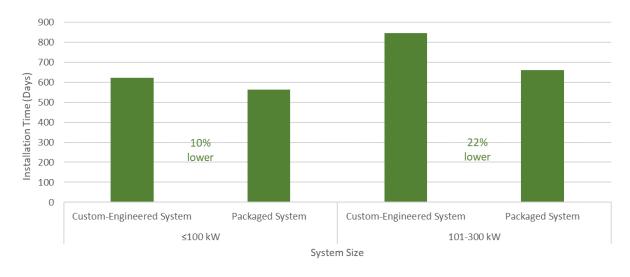


Figure 4. Installation time reductions for packaged CHP vs. custom-engineered systems in New York.

4. PACKAGED CHP MARKET PROFILE

Packaged CHP systems are well suited for facilities requiring electricity and standard hot water and/or chilled water outputs, with available indoor or outdoor space for the units. Packaged systems can be sized modularly and easily replicated for commercial and institutional facilities with similar building layouts and energy requirements. Packaged CHP systems can also be applied to light industrial facilities, but facilities with large thermal requirements for process heating or high-temperature steam will likely require a custom-engineered approach.

Packaged systems have expanded the CHP market to include more market sectors, including a variety of commercial, institutional, and multifamily facilities that can realize the efficiency, emissions, economic, and resilience benefits of CHP. The DOE CHP Installation Database¹³ and information from Packaged CHP Accelerator and eCatalog supplier partners were used to characterize CHP installations as packaged or custom-engineered systems. These data were used to assess trends in packaged CHP installations, including application types and size ranges.

Figure 5 shows the 12 market sectors with the highest number of new CHP project installations for 2000 through 2020, characterized as either packaged or custom-engineered systems. Applications such as multifamily buildings, schools, nursing homes, and hotels have primarily used packaged CHP systems. Other facility types have also installed more packaged CHP systems than conventional systems except wastewater treatment and agriculture applications, which often require custom biogas treatment equipment. Utility-operated CHP systems (including remote communities and downtown district energy applications) are also more likely to be custom-engineered compared with other applications.

Packaged CHP systems tend to have a smaller footprint than traditional custom-engineered systems, although packaged engines, microturbines, or fuel cells can be installed as modules for multi-megawatt systems. Project sizing varies by market application, with packaged systems in multifamily buildings and K-12 schools averaging under 130 kW in size, whereas packaged systems at hospitals averaged over 1 MW.

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¹³ https://doe.icfwebservices.com/chp

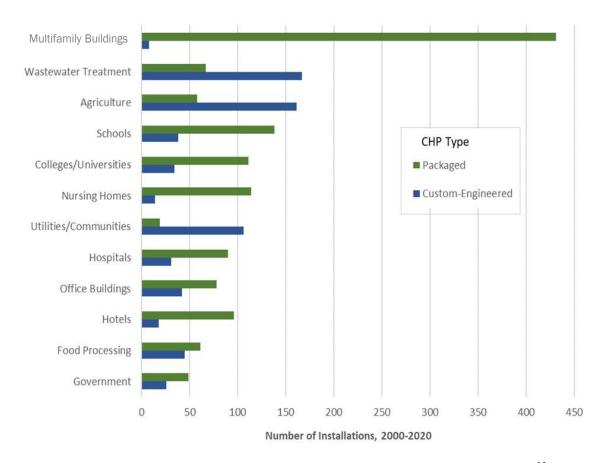


Figure 5. CHP by application, custom-engineered vs. packaged systems, 2000–2020.¹⁴

Packaged CHP offerings have opened up the market for smaller and nontraditional sectors. A large amount of CHP potential is available in commercial, institutional, multifamily, light manufacturing, government, and military applications. These markets have smaller facilities with minimal CHP experience and limited technical resources. Packaged CHP offerings with standard finance, service, and maintenance contracts can enable facility owners in these markets to minimize perceived risks and realize the benefits of onsite CHP.

As demonstrated in Figure 6, most of the packaged CHP systems installed in the United States to date are located in California and New York. Each of these states added more than 400 packaged CHP installations from 2000 through 2020 (416 for California and 567 for New York). Together, these two states represent more than half of the total US packaged CHP installations over this period. Massachusetts, New Jersey, and Connecticut have all added between 100 and 200 packaged CHP installations during the same time period, with all other states each installing fewer than 100 systems. High electricity prices in California and the Northeast, along with CHP Packagers' historic focus on these markets, have contributed to this trend.

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¹⁴ Based on ICF analysis of engines, microturbines, and fuel cell installations found in the DOE CHP Installation Database.

 $[\]frac{15}{\text{https://www.energy.gov/eere/amo/articles/new-release-us-doe-analysis-combined-heat-and-power-chp-technical-potential}$

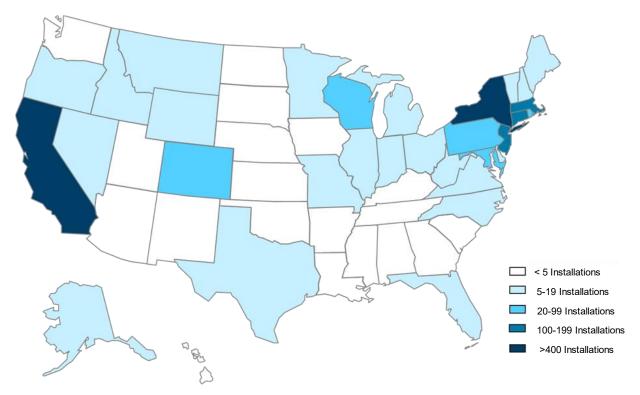


Figure 6. Packaged CHP installations by state, 2000–2020.¹⁵

Trends over time in the use of packaged CHP compared with custom-engineered systems in the DOE CHP Installation Database varied depending on the prime mover technology. Fuel cells and microturbines have always been primarily installed as standard CHP packages. However, reciprocating engine systems—the most common prime mover for CHP—shifted from primarily custom-engineered in the early 2000s toward predominantly packaged systems in the 2010s (Figure 7).

From 2000 through 2009, less than 50% of CHP engine installations were packaged systems; the majority were custom-engineered. By 2017, more than 90% of CHP engine installations were packaged systems, a trend that continued through 2020.

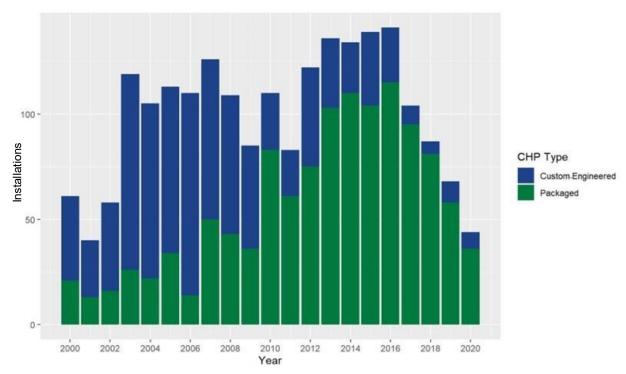


Figure 7. Packaged and custom-engineered CHP reciprocating engine installations, 2000–2020.¹³

As shown in Figure 8, California and the northeastern states dominated the market for packaged CHP engine systems in the early 2000s, gaining traction in other states by 2010 and further increasing throughout the 2010s.

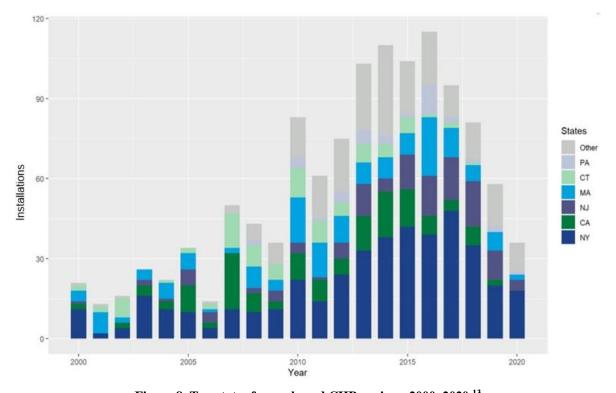


Figure 8. Top states for packaged CHP engines, 2000–2020.¹³

Packaged systems represented more than 85% of reciprocating engine CHP installations from 2016 through 2020. When including all prime mover technologies in the CHP Installation Database, packaged systems represented more than 70% of all CHP installations in this time period. The most common region and application for packaged CHP were northeastern states and multifamily buildings, respectively.

The data from the DOE CHP Installation Database indicate that packaged systems have enabled commercial and multifamily buildings to benefit from CHP installations. These sectors have a strong preference for packaged CHP systems over custom-engineered CHP systems, as evidenced by the low CHP installation rates before packaged CHP offerings were widely available. Additionally, the data demonstrate that packaged CHP systems have become the predominant type of CHP installation. Although a majority of fuel cells and microturbines have historically been installed as CHP packages, until 2010, most CHP reciprocating engines were installed as CHP packages instead of custom-engineered systems. By 2017, about 90% of CHP engine installations were packaged systems. The shift to packaged systems in CHP engines below 3 MW fundamentally transformed the CHP market, as reciprocating engines account for approximately 7 in 10 CHP installations in this size range. 13

Project Snapshot: Taylor Farms, Gonzales, California 16



Image courtesy of Concentric Power.¹⁶

Taylor Farms in Gonzales, California, is the largest fresh vegetable processor and marketer in North America. The packaged CHP system at the Gonzales processing facility is based on a 2 MW reciprocating engine generator set. The waste heat from the CHP plant powers a 240 -ton ammonia/water absorption refrigeration system that supplies ammonia refrigerant at 18°F to the processing facility. The CHP plant is a key contributor to its microgrid, which also features a wind turbine and solar photovoltaic panels. Taylor Farms saw a reduction of 12,190 metric tons of CO₂ emissions in one year—a 94% decrease from before the microgrid was completed.

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¹⁶ https://chptap.ornl.gov/profile/440/TaylorFarms-Profile.pdf

5. DOE PACKAGED CHP ECATALOG

NYSERDA ran a successful packaged CHP program for 7 years in New York. Lessons learned from the NYSERDA program experience suggested that a national eCatalog should include significant market engagement efforts to promote packaged CHP deployment, raise awareness of the benefits of CHP and of the eCatalog itself, and provide technical and market assistance to potential packaged CHP end users. DOE launched the Packaged CHP eCatalog in November 2019. The Packaged CHP Accelerator was initiated that same year to support the launch and use of the DOE eCatalog and to provide information on the ongoing development and enhancements to the eCatalog.

The eCatalog is designed to remove installation barriers, lower project costs and installation times, and reduce the perceived risk of installing CHP by offering comparable standardization of CHP system performance. Three key stakeholder groups in the eCatalog are as follows:

- ► CHP Packagers responsible for engineering, design, assembly, and testing of packaged CHP systems that meet DOE performance requirements in the eCatalog
- ► CHP Solution Providers responsible for installation, commissioning, maintenance, and service of DOE-recognized packaged CHP systems
- ► CHP Engagement Partners, including utilities, state energy offices, and energy efficiency program administrators that support CHP market development through targeted market awareness, technical assistance, and/or incentive programs

As of the end of 2022, the eCatalog included 340 recognized packaged CHP system offerings, 42 CHP Packagers (Figure 9; in some cases, Packagers also serve as Solution Providers), 26 CHP Solution Providers, and 18 CHP Engagement Partners. The eCatalog provides connections to the larger community of CHP stakeholders, including CHP trade allies and DOE's CHP TAPs.



Figure 9. CHP Packagers in the DOE Packaged CHP eCatalog—many are also Solution Providers.

The eCatalog program includes a rigorous review and recognition process designed to assure eCatalog users that recognized Packagers and Solution Providers have proven engineering, design, assembly, testing, and installation capabilities to provide and support packaged CHP systems that can be easily installed, commissioned as expected, and trusted to deliver stated performance. The review and recognition process for packaged CHP systems verifies that the system design and performance meet DOE requirements in terms of design efficiencies, system availabilities, and documented energy and emissions performance. Full- and part-load performance data, system schematics, and component details provide eCatalog users with sufficient performance and physical information to instill confidence in the packaged CHP system offerings. Detailed information on installation, commissioning, and maintenance procedures; documentation of stated performance and emissions; and applicable certifications are required for DOE internal review. Each requested review item is necessary to either convey to the eCatalog user the nature of the packaged CHP system or provide the DOE reviewers with sufficient information to verify the system design and operability of the package.

The eCatalog provides in-depth search capabilities that allow CHP users, consulting engineers, and others to sort the suite of available packaged CHP systems given a variety of site specifications and needs. After entering the facility zip code, which is required to initiate the search function, users can screen the CHP packages based on key items such as system size (in kilowatts), fuel type (e.g., natural gas, renewable natural gas [RNG], propane, digester gas, hydrogen blends), heat recovery requirements (hot water, steam, cooling, or any combination), and other system attributes such as prime mover type (reciprocating engines, microturbines, combustion turbines, back pressure steam turbines, and organic Rankine cycles), grid connection type (grid parallel only or grid island with black start capability), and physical constraints (length, width, height, and weight). All Packaged CHP eCatalog system performance data are based on DOE standardized performance requirements; for example, hot water is supplied to the site at 180°F and steam is provided at 15 or 125 psig saturated steam conditions. This standardization allows for a fair performance comparison between packaged CHP systems.

The eCatalog is focused on packaged CHP systems less than 20 MW individual system capacity and is updated on an ongoing basis to add additional packaged CHP systems, Packagers, and Solution Providers.

The eCatalog home page (Figure 10) offers a variety of features for users. The SITE GUIDE page provides an understanding of the basic functions of the catalog, as well as background information on CHP and packaged systems. The SEARCH eCATALOG feature allows users to conduct a search of packaged CHP systems commercially available in their zip code, yielding Systems Overview Cards (Figure 11) that can be saved, compared (Figure 12), and downloaded (PDF and Excel).

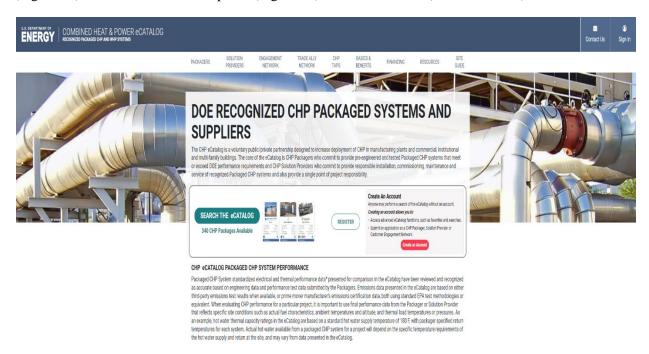


Figure 10. Home page for the DOE Packaged CHP eCatalog.

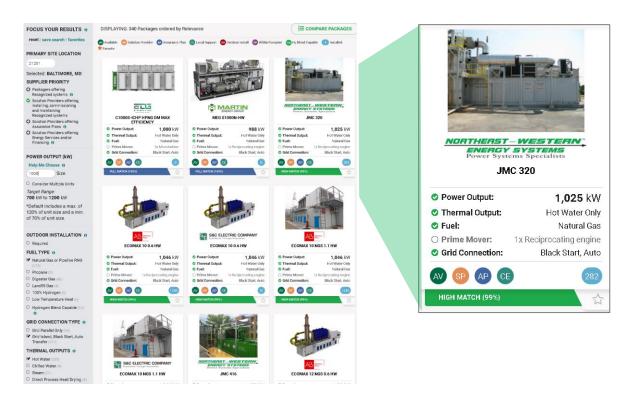


Figure 11. Packaged CHP system search results and system overview card.

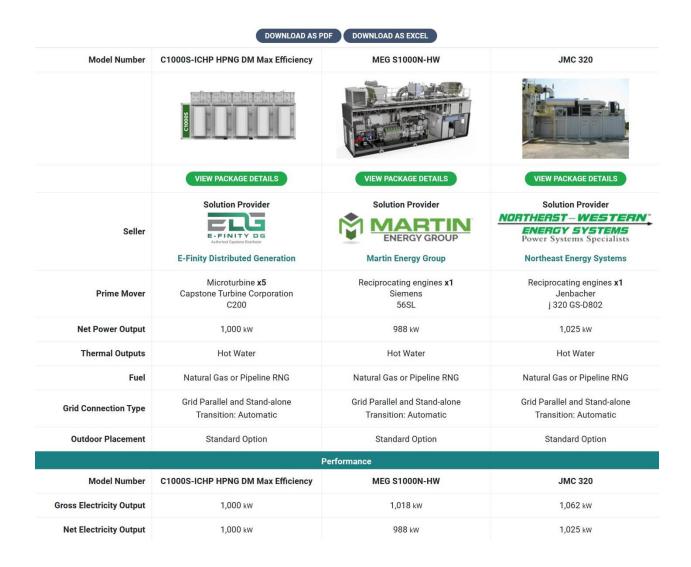


Figure 12. Packaged CHP system comparison (partial data listing).

Selecting the Packaged CHP System Overview Card (Figure 11) reveals detailed technical information about that system, including verified CHP performance data in terms of electricity and thermal energy output and efficiencies (Figure 13), supplier contact information, utility or state energy office CHP program information and contacts, and access to the DOE CHP TAP servicing the site ZIP code. All information can be easily saved or downloaded.

PERFORMANCE DATA



Performance data presented below is based on capacity that is available at the respective prime mover load conditions. Fuel data is in Higher Heating Value (HHV). Note that when multiple thermal capacities are presented e.g. hot water, steam, chilled water and/or ORC kW, these capacities are based on using all the thermal heat available from the prime mover and should be viewed as independent and not concurrent with other thermal capacities. Exception, for reciprocating engines steam production is generally using only exhaust heat so that hot water or chilled water capacity is concurrent with the steam capacity. All performance ratings are at sea level and adjustments should be made for operation at altitude, particularly for microturbines and combustion turbines. In all cases, contact the Packager or Solution Provider for site specific details.

		100% GROSS POWER 75% GROSS POWER		50% GROSS POWER						
	Ambient Temperature	95°F	59°F	0°F	95°F	59°F	0°F	95°F	59°F	0°F
	CHP Fuel Input (MMBtu per hour HHV)	10.3	10.3	10.3	8.0	8.0	8.0	5.7	5.7	5.7
	Gross Electricity Output (kW)	956	1,062	1,062	716	795	795	474	527	527
POWER	Net Electricity Output (kW) •	923	1,025	1,025	689	765	765	453	503	503
	Net Electric Efficiency % (HHV) 1	30.4	33.8	33.8	29.3	32.5	32.5	27.0	30.0	30.0
	Supply Temp to Site (°F)		180 °F			180 °F			180 °F	
	HW flow (GPM) 6	188	188	188	148	148	148	108	108	108
нот матек	Return Temp from Site (°F)	140	140	140	140	140	140	140	140	140
НОТ	Hot Water Capacity (MMBtu/hr)	3.77	3.77	3.77	2.98	2.98	2.98	2.17	2.17	2.17
	Thermal Efficiency % (HHV) •	36.5	36.5	36.5	37.2	37.2	37.2	38.0	38.0	38.0

*Be sure that the site thermal load will handle return water temperatures to the CHP system as stated. (e.g. 5 to 10 F below) Otherwise, hot water capacity will be less than stated. Contact the Packager/Solution Provider for details.

Figure 13. Packaged CHP system detailed performance information.

Other eCatalog tabs on the home page provide quick access to a host of DOE CHP activities and information:

- The BENEFITS tab provides a quick understanding of CHP and an overview of packaged CHP basics and benefits.
- The FINANCING tab describes common financing mechanisms for funding CHP projects with links to more detailed DOE resources and information on CHP financing.
- The RESOURCES tab contains a library of CHP case studies, CHP database information, tools, technology fact sheets, presentations, and webinars.
- The PACKAGERS and SOLUTIONS PROVIDERS tabs detail the roles and responsibilities of recognized suppliers in the eCatalog, include a list of recognized eCatalog suppliers that can be filtered by state, and provide access to detailed descriptions and contact information for each recognized supplier.

- The TRADE ALLY NETWORK tab lists companies that provide specific consulting services or licensed consulting engineering services for CHP systems.
- The CUSTOMER ENGAGEMENT NETWORK tab lists utilities and state agencies with CHP deployment and assistance programs and provides one-click access to key contacts and program information.
- The CHP TAPS tab showcases the 10 regional DOE CHP TAPs, coverage areas, and contact information.

THE FUTURE OF PACKAGED CHP

Packaged CHP systems are a part of the ongoing transition toward clean distributed energy resources. As the transition occurs, market needs will emerge that packaged CHP installations can fill. The following market trends are expected to contribute to future packaged CHP products and offerings:

- Expansion of packaged CHP product offerings especially for micro-CHP (less than 50 kW) applications
- ► Growth of RNG as a substitute for fossil natural gas
- ▶ Significant market interest in packaged CHP systems that can utilize hydrogen
- ▶ Potential to scale carbon capture and storage (CCS) for distributed generation applications
- Hybrid systems that combine packaged CHP with solar photovoltaic (PV) and battery energy storage systems
- ▶ Use of CHP to support resilience and reliability in renewable microgrids

MICRO-CHP

Opportunities are growing for smaller-capacity CHP products in nontraditional CHP markets, such as multifamily housing, nursing homes, schools, and small office buildings. Packaged CHP products are ideal for many of these applications, and vendors are responding with the introduction of more packaged systems in the micro (less than 50 kW) size range. As of December 2022, the eCatalog contained packaged CHP systems as small as 24 kW.

One barrier for micro-CHP products is their relatively high capital costs. In applications that are suitable for micro-CHP, customers are highly cost sensitive and are reluctant to invest in high-capital cost technologies, even if the payback is attractive. Consequently, for micro-CHP applications, hardware development trends will likely focus on cost engineering to reduce capital costs, and on system designs that facilitate easier, lower-cost installation in existing buildings and new construction.

6.2 **RNG**

Federal and state decarbonization policies are promoting interest in reducing the consumption of fossil natural gas. One alternative to fossil natural gas is to produce RNG by upgrading renewable biogas to pipeline quality standards. RNG (i.e., biomethane) has equivalent properties to fossil natural gas and can be injected into existing natural gas pipelines.¹⁷

Two common types of biogas are landfill gas and digester gas. Landfill gas is produced from the decomposition of organic material in landfills, and digester gas is produced from the anaerobic digestion of organic materials, including sewage sludge, animal manure, food, and industrial organic waste. 18,19 Landfill gas and digester gas have been used for many years to fuel distributed generation systems,

¹⁷ https://www.epa.gov/sites/default/files/2021-02/documents/lmop_rng_document.pdf

¹⁸ https://www.epa.gov/lmop/basic-information-about-landfill-gas

¹⁹ https://www.epa.gov/anaerobic-digestion/basic-information-about-anaerobic-digestion-ad

including CHP. Currently, more than 600 CHP systems operate on biogas in the United States, concentrated in wastewater treatment plants, farms, and industrial facilities located near landfills.¹³

RNG production is ramping up in the United States, and research from the American Gas Foundation found that RNG supplies could increase to an estimated 12%–28% of US gas consumption by 2040.²⁰ As the percentage of pipeline RNG increases, the carbon footprint for natural gas end use equipment, including packaged CHP installations, will decrease.

6.3 HYDROGEN

Renewable and/or net-zero hydrogen-fueled CHP can be a path to ultimately decarbonize thermal end uses in industrial and commercial facilities that are difficult and/or costly to electrify, as well as critical facilities and operations that need dispatchable onsite power for long duration resilience and reliability. Most hydrogen is currently produced by reforming natural gas. This type of hydrogen is sometimes referred to as *gray* hydrogen. If CCS is applied to gray hydrogen, the resulting product is often called *blue* hydrogen. A third designation is *green* hydrogen, which is a renewable form of hydrogen produced from water electrolysis using renewable electricity (Figure 14).

	Types of hydrogen	
Green Produced using electrolysis from renewable electricity	Blue Produced from natural gas reformation with carbon emissions captured and stored	Gray Produced from natural gas reformation (no carbon capture)

Figure 14. Color designations for hydrogen.²¹

Modern commercially available combustion turbine and reciprocating engine CHP systems can operate on hydrogen mixtures of 5% to 20% hydrogen without equipment modifications, and a few reciprocating engine manufacturers currently have products rated up to 40% hydrogen. Design changes are required to operate with hydrogen concentrations above 40%. At least one vendor is currently offering reciprocating engine CHP systems rated for 100% hydrogen. Most major reciprocating engine, combustion turbine, and microturbine vendors are expected to have 100% hydrogen-fueled products with comparable performance to current natural gas systems commercially available by 2030.

6.4 CCS

There are two fundamental approaches for reducing carbon emissions. As described, one approach is to transition from fossil fuels to low- or zero-carbon fuels. Another approach is CCS, which is used to reduce CO_2 emissions when a fossil fuel, such as natural gas, is burned. With CCS, CO_2 is separated from the combustion exhaust and then stored, typically by injecting the CO_2 into a deep underground geologic formation.²³

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²⁰ https://gasfoundation.org/wp-content/uploads/2019/12/AGF-2019-RNG-Study-Full-Report-FINAL-12-18-19.pdf

²¹ https://chpalliance.org/wp-content/uploads/2021/04/CHPA-Hydrogen-Webinar-Master-Deck,pdf

²² Current engines running on 100% hydrogen are derated up to 30% compared with natural gas engines when comparing fuel energy input to power output. Manufacturers are working to close this gap with new hydrogen engine designs.

²³ https://netl.doe.gov/carbon-management/carbon-storage/faqs/carbon-storage-faqs

Approximately a dozen CCS facilities are in commercial operation in the United States, and more than 30 pilot or demonstration projects are underway.²⁴ These projects have primarily been implemented at industrial sites with large CO₂ emissions, such as coal-fired power plants, fertilizer plants, chemical production facilities, natural gas processing facilities, and ethanol plants. According to a 2022 DOE report, the United States has more than 20 MTPA of operational carbon capture capacity, expected to increase to approximately 140 MTPA by 2030.²⁵

R&D efforts are underway to extend CCS to smaller applications, and in the future, CCS might be applicable to the upper capacity range of packaged CHP systems (e.g., megawatt-sized reciprocating engines or combustion turbines). 26,27

6.5 HYBRID SYSTEMS AND MICROGRIDS

Packaged CHP can be combined with other technologies such as PV and battery energy storage in hybrid systems, including microgrid configurations. Solar PV and battery energy storage are the most common technologies used with CHP in US microgrids.²⁸ In the future, standardized packaged CHP systems may be paired with these technologies.

Hybrid systems offer operational flexibility and allow end users to right-size onsite CHP and minimize fuel consumption and emissions. Although CHP provides a reliable baseload anchor, generating heat and power 24 hours a day, intermediate and peak loads for the facility or microgrid can be served by renewable PV and battery storage (Figure 15). Excess electricity from PV and strategic use of battery energy storage can also be used to participate in utility markets and provide services to the grid. During grid outages, the hybrid CHP system can remain fully functional, delivering necessary heat and power to the facility.

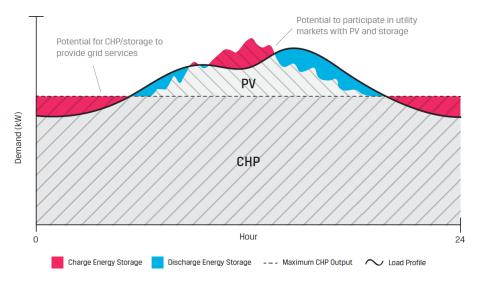


Figure 15. Hybrid system with CHP, solar PV, and battery energy storage²⁹

²⁴ https://www.catf.us/2021/03/carbon-capture-projects-around-the-world/

²⁵ https://liftoff.energy.gov/wp-content/uploads/2023/04/20230424-Liftoff-Carbon-Management-vPUB update.pdf

²⁶ https://www.bakerhughes.com/process-solutions/compact-carbon-capture

²⁷ https://www.carbonpoint.com/copy-of-carbon-negative-power

²⁸ https://doe.icfwebservices.com/microgrid

²⁹ https://www.icf.com/insights/energy/microgrid-technology-trends

7. SUMMARY

As experienced by end users in New York and elsewhere in the United States, packaged CHP systems have simplified the equipment selection and installation process for CHP, leading to increased deployment in nontraditional markets. Packaged CHP installations have allowed hundreds of facility owners to realize the efficiency, emissions, and resilience benefits of CHP.

Building on NYSERDA's early efforts to promote the benefits of packaged CHP, DOE's Packaged CHP Accelerator and eCatalog have further demonstrated the applicability and benefits of CHP.

- Packaged CHP systems reduce installation cost and time compared with traditional customengineered systems.
 - o Packaged systems over 100 kW achieved cost reductions of 24% and installation time reductions of 22%, compared with custom-engineered systems.
 - o Packaged systems smaller than or equal to 100 kW achieved cost reductions of 31% and installation time reductions of 10%, compared with custom-engineered systems.
- Packaged CHP systems have steadily gained market share compared with custom-engineered systems.
 - Prior to 2010, the majority of CHP installations were custom-engineered. Since 2010, the majority have been packaged.
 - From 2016 through 2020, packaged systems represented more than 85% of reciprocating engine installations and more than 70% of all CHP installations.
 - o From 2000 through 2020, multifamily buildings, schools, nursing homes, and hotels have almost exclusively installed packaged CHP systems rather than custom-engineered systems.
- ▶ The Packaged CHP Accelerator and eCatalog are helping to grow the packaged CHP market by promoting standard and prequalified CHP technology systems and vendors.
 - o From 2020 through 2022, the Packaged CHP Accelerator actively promoted participation in the eCatalog through webinars, conferences, and partner communications.
 - As of the end of 2022, the eCatalog included 340 recognized Packaged CHP System offerings, 42 CHP Packagers, 26 CHP Solution Providers, and 18 CHP Engagement Partners. Packaged CHP offerings in the eCatalog are available in every zip code in the United States.
- ▶ R&D for packaged CHP is leading to hybrid systems and alternative fuel capability that can be used to reduce carbon emissions.
 - Packaged CHP can be paired with PV and/or battery energy storage in hybrid configurations, providing long-duration energy resilience while minimizing fuel use and emissions.
 - Most major equipment manufacturers have initiated programs to develop prime movers (primarily reciprocating engines) for packaged CHP systems that can operate with 100% hydrogen fuel without performance penalties.

Packaged CHP systems are expected to remain an important technology for reliable onsite power, energy resilience, and decarbonization efforts. The resources developed by DOE's Packaged CHP Accelerator and eCatalog will provide valuable guidance and tools for end users, utilities, and energy industry stakeholders to enable continued benefits from packaged CHP installations.

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